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ORIGINAL SCIENTIFIC PAPER

Allometric Variation in Modern Humans and the Relationship Between Body Proportions and Elite Athletic Success

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Abstract

In many sports, greater height and arm span are purportedly linked to athletic success. While variation in body proportions has been explored across an array of scientific disciplines, studies focusing on humans of tall stature outside of clinical cases are limited. We investigated body size proportions in a sample of elite athletes, employing data on recruits for the National Basketball Association (NBA, n=2,990), mixed martial arts (MMA) fighters (mixed-sex, n=1,284), as well as a control sample of healthy young adults who are not professional athletes, represented here by male (n=4,082) and female (n=1,986) recruits for the United States Army, to test two hypotheses: 1) There is a significant difference in arm span to height ratios between elite professional athletes and the control population, and 2) There is a significant relationship between arm span to height ratio and athletic success within the NBA and MMA. We find that NBA players are significantly taller, with absolutely and relatively wider arm spans than MMA fighters and the control population. Additionally, we find that basketball players are significantly more likely to be drafted earlier in the NBA, and MMA fighters are significantly more likely to have a better loss to win ratio, if their arm span to height ratio falls above the regression line. However, we note that arm span and height, as well as athletic success, are impacted by a myriad of factors, and some of the most successful professional athletes do not have particularly long arms relative to their height.

Key words: *Arm Span, Height, Body Size, Basketball, Mixed Martial Arts, Stature*

Introduction

Human cultures have long celebrated athletic prowess, holding those who excel at feats of athleticism in high regard (Miller, 2005). Alongside this fascination has been a debate as to whether particular body shapes confer an advantage for different types of sports and/or provide an important marker for identifying potential success (Torres-Unda et al., 2013). Children today are often encouraged to participate in sports according to predisposed abilities perceived from their body shape (Sellers & Kuperminc, 1997). For example, in the United States many tall statured young people are channeled into athletics, particularly basketball, often with the goal of professional employment and a profitable career (Beamon & Bell, 2002; Sellers & Kuperminc, 1997). This practice may explain, in part, why modern athletes are on average taller than athletes were 50-100 years ago (Norton & Olds, 2001). In addition to height, a wide arm span (also referred to as wingspan or reach) has been considered important to athletic success (McCauley, 2018).

This focus on height and arm span raises questions about the interrelationship between them. The vast majority of research into human body proportions has focused on skeletal disorders and pathologies (Nwosu & Lee, 2008; Rappold et al., 2007). There has been substantial medical research on individuals of particularly short stature, defined as being more than two standard deviations below the average (Shea & Bailey, 1996), focused on individuals with skeletal and developmental abnormalities (Nwosu & Lee,

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2008; Rappold et al., 2007). However, the number of investigations into typical variation in limb proportions among people of particularly tall stature are few and far between, and are overwhelmingly focused on pathological height (Davies & Cheetham, 2014).

As for studies exploring the relationship between athletic success and body proportions, early research was largely bogged down by a preoccupation with ethnic and racial variation (Cureton & Hunsicker, 1941). Most recent studies focus exclusively on variation in standard body size measurements and their association with 'positions' within an athletic team (a center in basketball, for example) or success at particular sports (Ackland et al., 1997; Torres-Unda et al., 2013) without discussion of relative proportions or allometric variation and their potential effects on overall athletic success. Many of these studies have also been hindered by small sample sizes.

To address these two gaps in the literature, we compiled a large dataset of publicly available body size measurements for two groups of elite athletes competing primarily in the United States: basketball players scouted by the National Basketball Association (NBA) and mixed martial arts (MMA) fighters. These groups of athletes compete in sports where a wide arm span is highly valued, and they represent team sports (basketball) and individual sports (mixed martial arts). We compared these professional athletes to a control population of US Army recruits to test two hypotheses: 1) professional athletes have larger arm span to height ratios compared to the control population; 2) success among professional athletes within the NBA and MMA correlates with a larger arm span to height ratio.

Methods

Materials

Our sample includes n=2,990 elite male basketball players scouted for the National Basketball Association (NBA) and n=1,284 professional athletes (mixed sex) competing in mixed martial arts. We downloaded these data from the professional sports websites Draft Express (draftexpress.com) and Fight Metric (fightmetric.com). As a control population, we included data from n=6,068 United States Army recruits, measured as part of the ANSUR II (2012) Anthropometric Survey of US Army Personnel (Gordon et al., 2014). The sample of army recruits includes data for both males (n=4,082) and females (n=1,986), and represents the wide range of racial and ethnic backgrounds from which the United States military draws recruits. In total, the sample size is n=10,342.

Previous studies on smaller samples of humans have found significant differences in height, and arm span to height ratio, between males and females (Nadankutty et al., 2014). Therefore, we analyzed the US Army recruits separately by sex. Sex-specific data were not available for the MMA athletes and the basketball data only include males.

The body size of both groups of athletes and the USA recruits was measured by medical staff when they were scouted or drafted into the professional leagues, or enlisted in the army, respectively. We focused on two body size traits. We included height (stature) and arm span for all three groups. Arm span is measured from fingertips to fingertips when the arms are extended laterally and held parallel to the ground (Gordon et al., 2014).

In order to assess the relationship between athletic success and body size proportions in NBA players and MMA fighters, we generated a metric of athletic success for each group (Table 1). For NBA players, the draft pick was used as a measure of athletic success leading up to entry into the profession (n=731). For MMA fighters, the loss to win ratio was calculated and used as a measure of athletic success (n=1,283), where a lower number indicates greater success. Using the loss to win ratio mathematically ensures that the athlete will have won at least one match in their career, and permits inclusion of athletes who have never lost a fight. The MMA loss to win ratio allows for a more direct indication of athletic success than does NBA draft number, but given that basketball is a team sport, the draft pick provides one of the only individualized numerical assessments in a basketball player's career. However, draft pick is likely influenced in part by an athlete's measured arm span, and results need to be considered with that caveat in mind. Both the draft pick and loss to win ratio were log-transformed to account for non-normal distribution of data.

Table 1. Mean athletic success by group

Group	N	Statistic	Mean
NBA	731	Draft pick	28.71
		LogDraft	1.32
MMA	1,283	Losses	5.21
		Wins	14.60
		LWR	0.37
		LogLWR	-0.45

Note. Abbreviations as follows: NBA is National Basketball Association, MMA is mixed martial arts, N is sample size, LogDraft is the log-transformed draft pick, LWR is loss to win ratio, LogLWR is log-transformed loss to win ratio. Note that statistics of athletic success are not available for the full sample.

Statistical analysis

All statistical analyses were conducted in R Statistical Environment version 3.2.3 (R Core Team, 2015). We generated descriptive statistics of the traits using the summary and describe functions in the *psych* package (Revelle, 2015), and we calculated coefficient of variation using default mathematical language in R (R Core Team, 2015). We ran a one-way MANOVA to compare the sample phenotypes across groups using the manova function. We calculated correlation coefficients between arm span and height using the rcorr function in the *Hmisc* package (Harrell & Dupont, 2012). In order to compare traits of interest, we conducted a linear regression using the lm function for each group separately and as a combined sample, producing coefficients of determination (R^2), as well as slope equations for each group. Additionally, we applied an ANCOVA to test for the effect of height on arm span and compare linear regression lines across the groups. All bivariate plots were produced using the ggplot function in the *ggplot2* package (Wickham, 2009).

Results

Basketball players scouted for the NBA have the longest arm span, the greatest height, and the largest arm span to height ratio of the four groups sampled for this study (Table 2). On the other end of the spectrum, female Army recruits are shorter and have a shorter arm span and smaller arm span to height ratio than male recruits, MMA fighters (mixed-sex), and basketball players. Height and arm span are significantly different across all four groups (MANOVA, $p<0.001$). Arm span to height ratio is also significantly different across groups (MANOVA, $p<0.001$). Male Army recruits have a larger average arm span to height ratio than MMA fighters, although arm span and height are both significantly higher in MMA fighters than Army recruits, male or female. Of the groups sampled, sex-specific data were available only for the Army recruits. Comparison using MANOVA finds that male Army recruits are significantly taller and have significantly wider arm span and larger arm span to height ratios than do female recruits (Table 2, $p<0.001$).

Table 2. Descriptive statistics for the study groups

		HEIGHT (cm)			ARM SPAN (cm)			AHR		
Group	**N**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Basketball	2,990	195.90	9.09	4.64	206.69	10.79	5.22	1.06	0.03	2.81
MMA	1,284	178.35	8.51	4.77	182.55	10.22	5.60	1.02	0.03	2.65
USA (M)	4,082	175.62	6.86	3.90	181.42	8.46	4.67	1.03	0.03	2.65
USA (F)	1,986	162.85	6.42	3.94	166.03	8.30	5.00	1.02	0.03	2.87
COMBINED	**10,342**	**179.37**	**14.02**	**7.81**	**185.91**	**17.27**	**9.29**	**1.04**	**0.03**	**3.03**

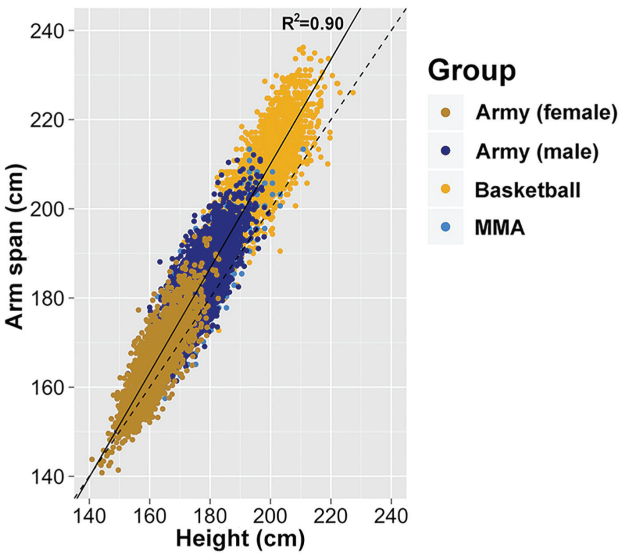
Note. Abbreviations as follows: MMA is mixed martial arts, USA is United states Army, M is male, F is female, AHR is arm span to height ratio, N is sample size, SD is standard deviation, CV is coefficient of variation.

Arm span is significantly correlated with height ($r=0.95$, $p<0.0001$) and height significantly predicts arm span ($R^2=0.90$, $p<0.0001$) in a pooled sample including all four groups (Figure 1). Bivariate regression between arm span and height produces slightly different regression lines with different intercepts for each group (Table 3). However, comparing the regression slopes between basketball players, MMA fighters, and Army recruits finds no significant difference (ANCOVA, $p=0.262$). The relationship between arm span and height is not isometric, but rather reflects an allometric effect: taller people have relatively wider arm spans than do shorter people. In all four groups, arm span is on average greater than height and is tightly constrained, with arm span to height ratio ranging from 0.94 to 1.12 (CV=3.03).

Table 3. Results of the linear regression analysis

Sample	Intercept	Slope[a]	R^2	P-value
Basketball	10.80	1.00	0.71	< 2.2e-16
MMA	-6.42	1.06	0.78	< 2.2e-16
USA (M)	2.94	1.02	0.68	< 2.2e-16
USA (F)	-6.36	1.06	0.67	< 2.2e-16
COMBINED	**-24.19**	**1.17**	**0.90**	**< 2.2e-16**

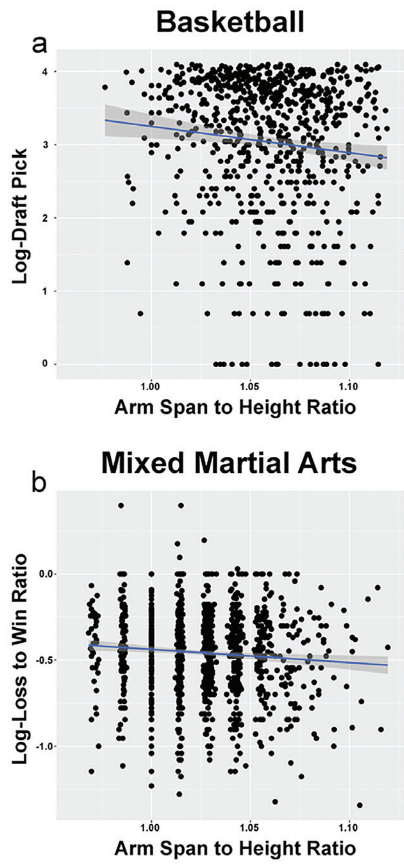
Note. Abbreviations as follows: MMA is mixed martial arts, USA is United States Army, M is male, F is female, R^2 is the coefficient of determination.
[a] Slopes are not significantly different between groups (ANCOVA, $p=0.262$).



Legend: The solid line represents the regression line ($y=1.17x-24.19$) and the dashed line represents the 1:1 line ($y=x$). Arm span and height are significantly correlated across groups ($r=0.95$, $p<0.001$), and height significantly predicts arm span ($R^2=0.90$, $p<0.001$).

Figure 1. Linear regression comparing arm span and height across all four groups sampled

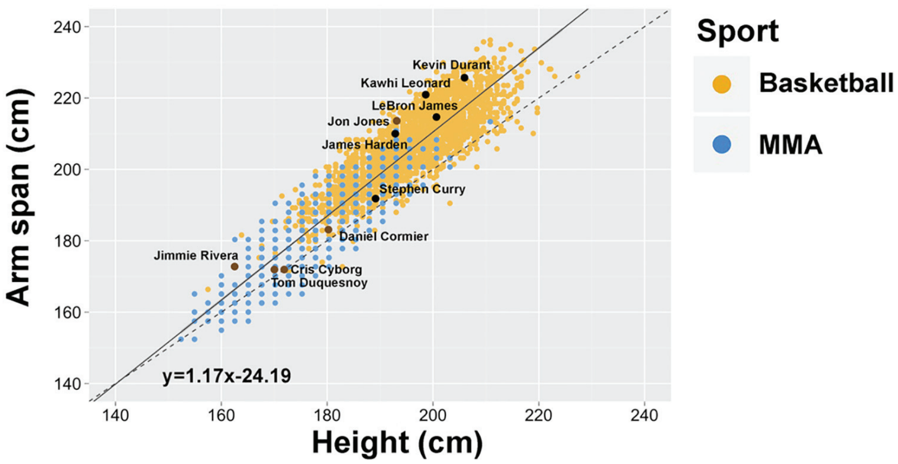
Linear regression finds that arm span to height ratio significantly predicts athletic success in NBA players (R^2=0.007, p= 0.016) and MMA fighters (R^2=0.008, p= 0.0007, Figure 2).



Legend: a) Arm span to height ratio and log-transformed draft pick in NBA players, b) Arm span to height ratio and log-transformed loss to win ratio in MMA fighters. Larger arm span to height ratio is significantly associated with a lower draft pick (a) or lower loss to win ratio (b). See text for definitions of athletic success.

Figure 2. Linear regression comparing arm span to height ratio with measures of athletic success

To further explore performance at the very highest level, we chose the top five athletes in each sport sampled, using loss to win ratio for MMA, and rankings by Sports Illustrated 2018 (Golliver & Mahoney, 2017) for the NBA, and highlighted their distribution around the regression line (Figure 3). Four of the top five NBA players (LeBron James, Kevin Durant, Kawhi Leonard, and James Harden) sit above the regression line of arm span to height, while Stephen Curry sits below the regression line for people sampled here. Among MMA fighters, Jon Jones and Jimmie Rivera sit above the regression line, while Daniel Cormier, Cris Cyborg, and Tom Duquesnoy sit below the regression line.



Legend: See methods for elaboration on choice of top athletes. The solid line represents the regression line (y=1.17x-24.19) and the dashed line represents the 1:1 line. Height significantly predicts arm span in athletes sampled (R^2=0.85, p<0.001).

Figure 3. Bivariate plot with linear regression comparing arm span and height in basketball players and MMA fighters, with the top five athletes in each sport highlighted and labeled (black for basketball and brown for MMA)

Discussion

From an evolutionary perspective, variation in limb proportions is key to variation in locomotion across our primate relatives and in mammals more broadly (Jungers, 1985). Humans are highly unusual compared to other great apes because of our ability to stand and walk upright efficiently (Jungers, 1985). Compared to our fossilized ancestors who lived 4 million years ago, humans today are taller (on average) and have relatively longer legs and shorter arms (Ruff, 2002). Modern human limb proportions and stature evolved by 1.5 million years ago in *Homo erectus* (Ruff, 2002; Walker & Leakey, 1993) along with the ability to walk bipedally as efficiently as modern people (Lordkipanidze et al., 2007). One of the phenotypic correlates of bipedalism is the decoupling of fore - and hindlimb proportions, such that arm span in humans is more independent from leg length than in other non-ape primates (Young et al., 2010). The archaeological record indicates that human height was fairly stable from 100,000 to 50,000 years ago and has since experienced a small decrease in average stature (Formicola & Giannecchini, 1999; Ruff et al., 2002). Humans today are highly variable in body size and shape, and the relationship between stature and arm span has been found to vary between human populations due to both environmental and genetic factors (Popović et al., 2015; Ruff, 2002). As a global average, arm span generally exceeds stature, although in some populations arm span is very close and sometimes even less than stature (Popović et al., 2015; Stulp & Barrett, 2016).

Our large scale analysis of data representing populations of diverse ancestry reveals that arm span and height are tightly correlated. This observation accords with those of previous studies that relied on smaller samples but found comparable correlations (r=0.73 to 0.89) between arm span and height (Reeves et al., 1996) as well as comparable arm span to height ratios (1.00 to 1.04) in adolescents (Reeves et al., 1996), elite MMA fighters (Kirk, 2016), and basketball players (Gryko et al., 2018). Human height is a complex trait, with dozens of genes implicated in normal height variation (e.g., Yang et al., 2010). The significant correlation between arm span and height strongly suggests that this covariation results from pleiotropic effects.

We also find that the four categories (basketball players, MMA fighters, and male and female Army recruits) differ significantly from each other in terms of arm span, height, and arm span to height ratio. Basketball players are, on average, significantly taller and have significantly wider arm span and a larger arm span to height ratio than MMA fighters and Army recruits. Mixed martial arts fighters, while shorter than elite basketball players, are significantly taller than non-athletes (represented here by both male and female Army recruits, analyzed separately), with a significantly wider average arm span. Given the strong evidence of a positive allometric effect, in which arm span to height ratio increases with height, these differences between the four groups are more likely explained by differences in height, with differences in arm span increasing in an allometric fashion.

This allometric relationship between arm span and height is likely driven by the positive allometry of the distal limb elements specifically. Previous studies have shown that the ulna and radius of the arms exhibit positive allometry, while proximal limb segments exhibit isometry, or slight negative allometry with stature (Auerbach & Sylvester, 2011). This means that taller individuals have lower arms that are proportionally longer, relative to overall arm length, than do shorter individuals. Long fingers, which have also been found to be associated with taller individuals (Meadows & Jantz, 1992), likely also contribute to the allometric relationship observed here. Using the ANSUR data (Gordon et al., 2014), we compared hand length and stature and found that these traits are significantly correlated in men ($r=0.67$, $p<0.001$) and women ($r=0.65$, $p<0.001$).

In regards to athletic success, we find a significant association between athletic success and arm span to height ratio in our sample, as defined by draft pick in the NBA, or loss to win ratio for MMA fighters. Among these professional athletes, individuals with larger arm span to height ratios are significantly more likely to achieve athletic success as measured by these metrics. For MMA fighters in particular, these results contradict smaller studies that have used alternate metrics of athletic success, such as rankings (Kirk, 2016). Informal studies have previously reported that NBA players with the largest arm span to height ratios are not the 'best' players (Zetterberg & Hallmark, 2011). We also find that some of the highest ranked and most recognizable athletes have body size proportions that sit below the regression line, moreso in MMA than the NBA.

Overall, successful athletes do tend to have a significantly wider arm span relative to their height, but these proportions are not outside the expected range of normal human variation. Having a larger arm span to height ratio may be significantly associated with athletic success, but it is widely recognized that athletes are successful due to a range of genetic, developmental, behavioral, environmental, and socioeconomic factors (Huffman & Cooper, 2012; Lindner et al., 1991). Minor variation in body proportions, especially at the most elite levels, is unlikely to be predictive of athletic success, but does seem to confer a slight advantage.

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Conflict of Interest
The authors declare that there are no conflicts of interest.

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